High Resolution Seismic Reflection Interpretations of the Hood Canal-Discovery Bay Fault Zone, Puget Sound, Washington

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Introduction

Hood Canal, an elongate, 75 km-long, two- to five-km-wide, northeast trending deep-water trough, defines the western limit of the Puget Sound estuary complex (Figure 1). This glacially and subglacially-carved feature, one of many channeled landforms occupying the Puget-Fraser Lowland, is filled with thick Quaternary deposits of unconsolidated and semi-consolidated glacio-lacustrine, glacio-fluvial, and transgressive marine sediment (Eyles et al., 1990; Mullins et al., 1990; Booth and Hallet, 1993). The abundance of sediment blanketing the Puget Lowland coupled with dense vegetation and the expansive marine waters of Puget Sound, make geologic interpretations of buried crustal structures difficult without the aid of land and marine seismic methods, remote sensing technology, and drill hole data.

The enigmatic "Hood Canal-Discovery Bay fault zone" is depicted as a northeast trending, ~75 km-long, continuous fault line beginning north of Hoodsport and following Hood Canal's shoreline north before curving north-northwest through the head of Dabob Bay (Figure 1) and continuing onshore into Discovery Bay (Johnson et al., 1996). Cascadia subduction zone studies have proposed that strike-slip fault displacement affecting large regions of the forearc, may accompany and/or follow large subduction earthquakes (Wang et al., 1995). Consequently, it is important to further define the specific type and lateral extent of faulting patterns in Hood Canal. Combining this information with known sediment thickness allows a quantifiable estimate of the areas seismic potential (i.e., relative resistance to seismic shaking) to be made. Although varying in success, some efforts have been made to address this issue. Dane et al. (1965) used gravity and earthquake data to propose that Hood Canal was a "...major active fault..." separating Puget Sound from the Olympics. Marine seismic reflection lines run through northern Hood Canal and southern Dabob Bay were used along with drill hole data to generate sediment thickness contours along sections of Hood Canal's western shoreline (Yount et al., 1985). A seismic reflection line run across the south end of Toandos Peninsula by Harding et al. (1988a) underwent preliminary post-processing and was later published as a USGS Open File Report (Harding et al., 1988b). This report included a crude interpretation of faulted Tertiary bedrock with ~350 m of apparent vertical offset. Gower et al. (1985), Johnson et al. (1994), and others have suggested that the southernmost strand of the east-west trending Seattle fault, shown terminating ~10 km east of Hood Canal, may continue west and be truncated by the Hood Canal fault. Most recently, Pratt et al. (1997) depict Hood Canal as a right-lateral strike-slip fault that forms the western border of their 14 to 20 km-deep, south-dipping Puget Lowland "thrust sheet" model.

The purpose of this study is to interpret the shallow (<0.7 km) seismic character of the Hood Canal-Discovery Bay fault zone. The data set consists of approximately 100 km of single-channel, high-resolution airgun seismic data collected on April 4–5, 1994 onboard the University of Washington's *RV Thomas G. Thompson*. Particular emphasis is placed on defining Hood Canal and southern Dabob Bay's Holocene and late Pleistocene sediment thickness patterns, recognizable fault structures, and crustal deformation possibly related to the Seattle fault zone.

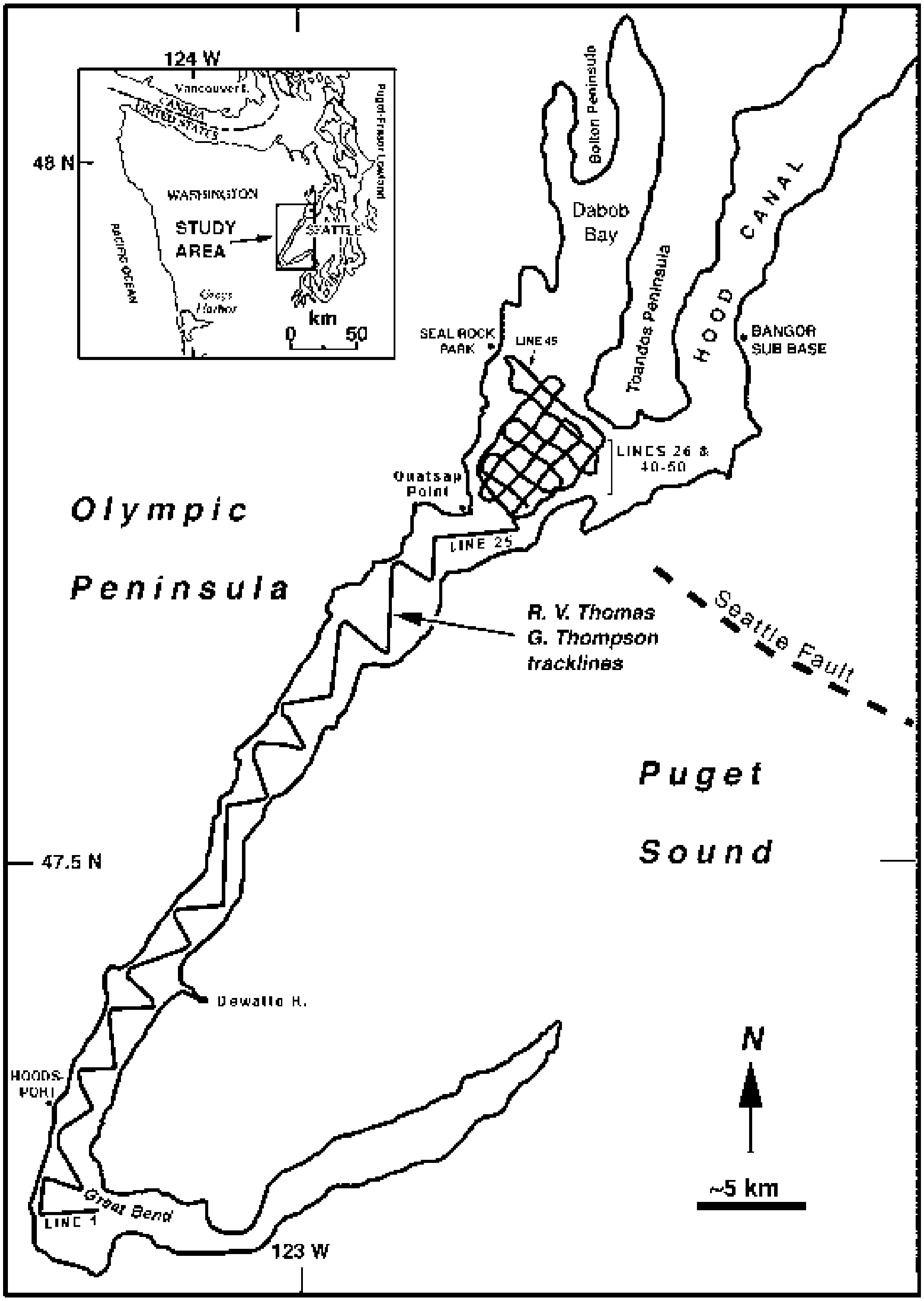

Figure1. Hood Canal study area.

Regional Geology

The Puget Lowland is located approximately 230 km east of the active Cascadia subduction zone. It lies within a broad forearc basin that extends south from the Fraser Lowland-Georgia Depression of British Columbia to Oregon's Willamette Basin. Bordering the lowland to the west is Paleocene to late Eocene rocks of the Coast Range Volcanic Province (CRVP). To the east are Mesozoic and Paleozoic terranes of the active Cascade Range. In western Washington's Olympic Mountains, basalt flow sequences of the 62–48 million year-old (Ma) Crescent Formation reach up to ~17 km in total thickness (Babcock et al., 1992). Along with the Metchosin Igneous Complex of British Columbia and Oregon's Roseburg and Siletz River Volcanics, the Crescent forms the "Coast Range basement," the earliest of three main periods of Coast Range volcanism (Snavely and MacLoed, 1974). This basement rock underlies most of western Washington and is thought to comprise a continuous crustal block that extends eastward from the Olympic Peninsula to the longitude of Seattle, Washington (Finn, 1990; Finn and Stanley, 1997). The easternmost edge of this crustal block lies concealed beneath thick glacial deposits and forms a major north-trending structural boundary separating rocks from the Coast Range and Cascade terranes. It is approximately located by juxtaposing fault lines of the north-northwest trending Coast Range Boundary and Southern Whidbey Island faults (Johnson et al., 1996).

The Olympic Accretionary Complex

Rocks of the Olympic Peninsula cover ~15,000 km^2 of northwestern Washington and form a crude triangle bordered by the Pacific to the west, Hood Canal to the east, and the Strait of Juan de Fuca to the north. The peninsula has two major geologic terranes, the "core" and "peripheral" rocks (Tabor and Cady, 1978). The core rocks include Eocene to Miocene marine sedimentary rocks with minor interbeds of pillow basalt, some of which are metamorphosed to prehnite-pumpellyite and greenschist facies (Babcock et al., 1992). For at least the last 40 million years (m.y.) (Wang et. al., 1995) the mountainous Olympic core rocks have been subjected to accretionary prism-style deformation; a result of underthrusting by the Juan de Fuca plate beneath North America. Making up the horseshoe-shaped belt of peripheral rocks are thick sequences of east-dipping Crescent basalt overlain on the north, east, and south by upper Eocene to Pliocene marine sedimentary rocks. The Crescent basalt that lines much of Hood Canal's western shoreline is a mechanically strong lithologic unit. This is indicated by its lack of seismicity (Dewberry, 1996), great thickness, and general lack of deformational structures like those seen in the Olympic core rocks. However, during accretion of the core rocks, this rigid basalt mass likely developed compensating fault structures (e.g., "tear faults"). Final isostatic uplift of the Olympic Peninsula at about 17 Ma resulted in the present structural orientation of the east-dipping to near-vertical Crescent basalt flow sequences (Tabor and Cady, 1978).

Quaternary Glaciation

Cordilleran Ice Sheet advances into western Washington occurred at least five times during the late Quaternary (Thorson, 1996). Fed by alpine glaciers in the Canadian Coast Range, the tidewater "Juan de Fuca lobe" advanced westward into the Strait of Georgia and eventually southward into the Puget Lowland as the "Puget lobe". Ice completely filled the Puget Lowland between the Olympic Mountains and Cascade Range. Following the most recent Fraser glaciation maximum (~15 thousand years ago [ka]), deglaciation of the Juan de Fuca-Puget lobe system was rapid and complete by ~13.5 ka, leaving behind an extensive low-gradient outwash plain termed the "great lowland fill" (Booth, 1994). Following deglaciation was an intense, but relatively brief period of isostatic uplift-induced crustal seismicity (Thorson, 1996). The primary source of this seismicity were crustal blocks located along pre-existing structural discontinuities, particularly those oriented perpendicular to ice flow directions and parallel to ice margins (Thorson, 1996). Present-day Hood Canal, oriented parallel and just up-glacier from the former Puget ice lobe's western margin, would have been ideally suited for the maximum expression of postglacial faulting (Thorson, 1996).

Puget Lowland Seismicity

Today, the central and northern Puget Lowland displays two general zones of seismicity (Symons and Crosson, 1997). The first, a diffuse zone within the North American plate and above ~35 km; and the second, a deeper zone (~40–70 km) within the obliquely subducting (rate of ~40 mm/yr; N68_E direction; Savage et al., 1991) Juan de Fuca plate. Beneath Puget Sound, crustal earthquake epicenters are generally confined to the glaciated area with a strong correlation between earthquake depth and glacial loading (Thorson, 1996). Noting paleoseismic evidence for Holocene displacement on the Seattle fault, Thorson (1996) suggests this correlation may represent a return to a pre-glacial "background" and more seismically active regional tectonic setting, a setting in which the transfer of subduction zone stresses in the forearc is not modulated or stabilized by glacial loading. Aprea et al. (1998) showed that crustal seismicity occurs only within the Crescent Formation basalt underlying the Seattle basin. They suggest that thick (>30 km) Crescent volcanics may effectively prevent the subduction of Olympic core rocks and help explain the concentration of crustal earthquakes beneath the Puget Lowland.

Local Geology

Detailed geologic mapping along the west and north-northeast shoreline of Hood Canal was done by Carson (1976a, 1976b) and Birdseye (1976). To date, no detailed geologic maps are available for the eastern shoreline of Hood Canal. The western side of Hood Canal dominantly comprises upper to lower Eocene basalt, interbedded conglomerate, and minor sedimentary deposits of the Crescent Formation. Outcrops of dark brown, columnar and massive Crescent basalt with flow tops dipping east at angles of ~10_–35_ are especially common along the mid-to-northern shoreline (Carson, 1976a, 1976b). However, basalt flows in the Dosewallips River valley, which drains into western Hood Canal, are oriented "…near vertical with tops facing east" (Babcock et al., 1992).

Overlying the Crescent is Oligocene (?) Twin River Formation volcanoclastics and pre-Fraser deposits of Olympia and Puget lobe glacial tills and outwash along with non-glacial sediments. Variably thick layers of Pleistocene Fraser glaciation sand and gravel tills, proglacial lacustrine silt, sand, clays, glacial drift, and outwash deposits are found throughout the area. Exposed Holocene deposits include alluvial fan sands and gravels, and older deglaciation to younger (<50-year-old) landslide deposits (Carson, 1976a, 1976b). The Toandos Peninsula (Figure 1) forms the eastern shoreline of Dabob Bay and is covered by thick Fraser advance outwash and lodgement tills with no mapped outcrops of Crescent basalt (Birdseye, 1976).

Seattle and Saddle Mountain East Faults

Both the Seattle and Saddle Mountain East faults show either direct or paleoseismic evidence for late Quaternary movement (e.g., Wilson et al., 1979; Johnson et al., 1996). The Seattle fault zone consists of four south-dipping, generally east-west trending fault segments with dominantly reverse or thrust displacement (Johnson et al., 1994). Throughout the Quaternary and possibly much of the Tertiary periods, fault strands of the Seattle fault zone have been subject to extensive fault displacement. Most notably, a ~7 m vertical offset along strand two of the Seattle fault which triggered a strong earthquake 1100 yrs ago (Atwater and Moore, 1992; Bucknam et al., 1992; Jacoby et al., 1992; Karlin and Abella, 1996; Schuster et al., 1992). The Saddle Mountain East fault is located ~5 km west of Hood Canal's Lilliwaup Creek. This 1.8 km-long fault scarp parallels Hood Canal, strikes N22_E, dips at 75_ to the SE, and exhibits 3.5 m of reverse dip-slip displacement dated at ~1,155 years ago and possibly coeval with displacement along the Seattle fault zone (Wilson et al., 1979). It is one of several crustal faults in this area thought to have developed during complex faulting and doming of the Olympic Peninsula.

Methods

The ~100 km of seismic track lines are shown in Figure 1. Trackline turn angles were limited to 50° to avoid difficult ship maneuvers, minimize hydrophone streamer drift, and facilitate smooth transition between adjoining track lines. NAVSTAR Global Positioning System (GPS) fixes, with an estimated positional accuracy of ± 50 m, were recorded and tagged on the seismic records at one minute intervals resulting in ~8.0 positional fixes/km. Water depth (accuracy of 1.0% water depth) and 3.5 kHz sub-bottom bathymetry were continually recorded. The ship's speed was maintained at <4.5 knots throughout the survey.

The sound source was a single 655 cm^3 (40 in^3) Bolt PAR 600B air-gun with an inlet pressure of 124 bar (~1800 psi), firing at a 2.2 second interval, and towed 70 m directly aft of *RV Thomas G. Thompson*. An AQ-1 titanate-zirconate, 200-element streamer (15 cm-spacing) was deployed from a four m-long boom extending off the ship's port quarter. The airgun was maintained at a tow depth of about 6 m and the streamer at approximately five m. The low and high band streamer signals (30–90 and 40–120 Hz) were routed through 30 dB amplifiers and displayed on separate channels of an EPC 9600 digital thermal graphic recorder (one and two sec sweeps). Digital audiotape (DAT) was used to record the raw acoustic, trigger signal, and amplifier data.

Data set post-processing took place over a four-day period at the University of Washington, Seattle with Dr. Thomas L. Pratt (USGS). Raw DAT tapes were played back with a TEAC DAT recorder, re-formatted from tape analog to digital format, and then re-digitized into seg-y format (2000 samples/sec) using the USGS data acquisition software program "MUDSEIS." The data set was then band-pass filtered at 10, 20, 160, and 320 Hz, deconvolved, gained (amplitude-balanced), migrated, and displayed as Postscript files using a UNIX-based workstation. After processing, Geologic structures observed in the records were line-drawn using graphics software. Seismic stratigraphic unit contacts were correlated using a scaled fence diagram. Additionally, a detailed bathymetry data set (~130 data points/km^2) covering mid-to-southern Hood Canal was obtained from the NOAA facility at Sand Point, Washington.

Results

Due to space and size limitations only two seismic profiles are included along with both an isopach map and inferred fault map for tracklines 40–50 (see Figure 1). For reference when viewing Figures 2 and 3, "M1" and "M2" designate first and second reflection multiples; "Qh" denotes Quaternary and Holocene glacial-marine sediments; and "Cr" refers to Crescent Formation bedrock (see text for description).

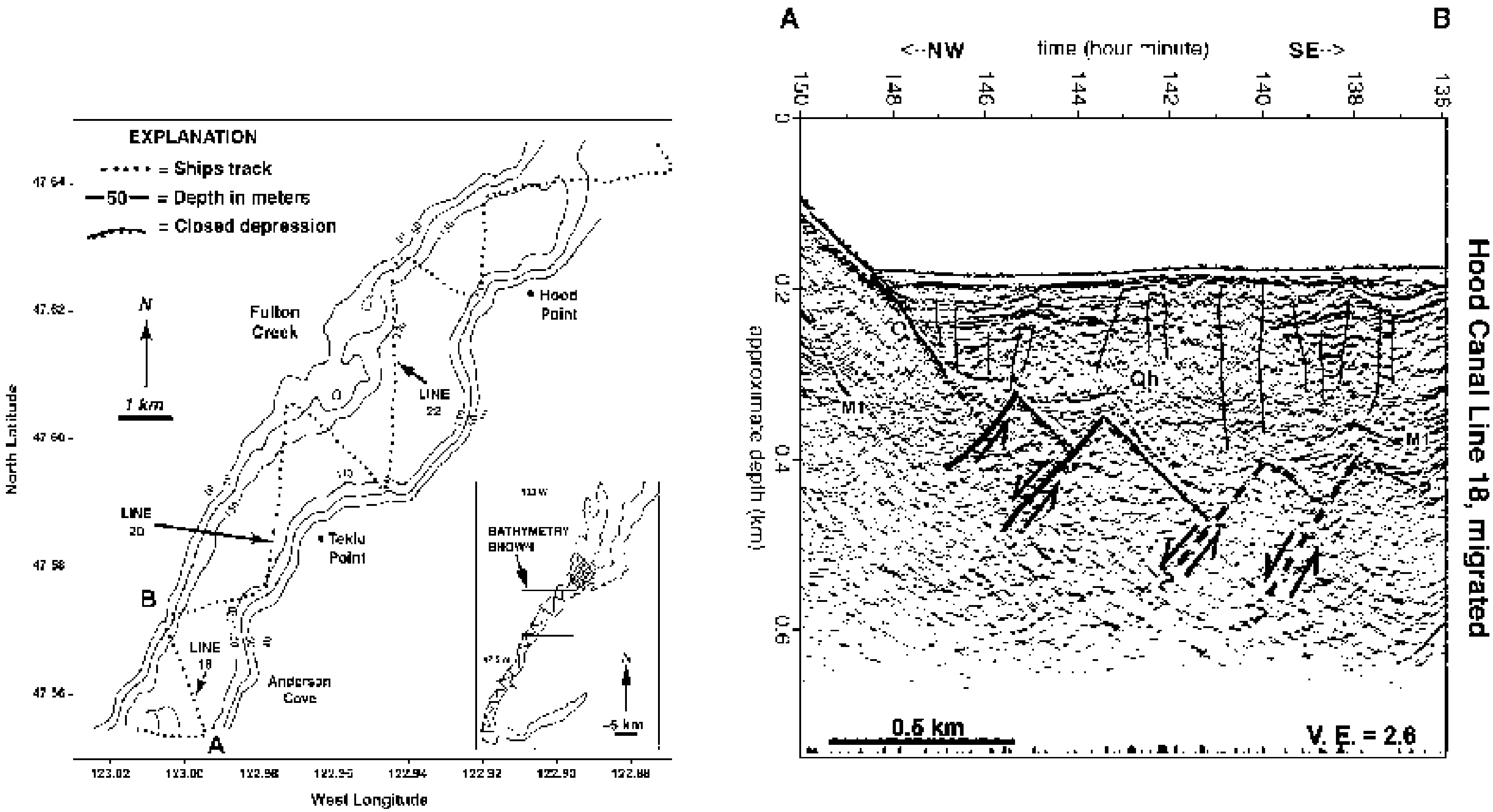

Figure 2. Interpreted seismic profile, trackline 18. This profile crosses Hood Canal beginning on the east shoreline (approx. latitude of Cummings Point) and ends on the western shoreline directly across from Anderson Cove (see "line 18," Figure 1). A ~20–50 m-thick, well-stratified, parallel reflector caps ~250 m of acoustically discontinuous and unstratified glacial sediment. Obvious normal faulting is observed in the steeply east-dipping Crescent basalt unit. The "hard reflector" filling and draping the fault block "V's" may be a compact basal till. The current fault block orientation may reflect a strike-slip or thrust fault stress component. Fault planes are dashed where unclear. Upward propagating faults within the sediment fill are indicated. Additionally, a pressure-ridge structure may be visible close to the surface layer (upper right, Figure 2). This type of compressional feature typically forms between multiple fault traces of strike-slip fault zones.

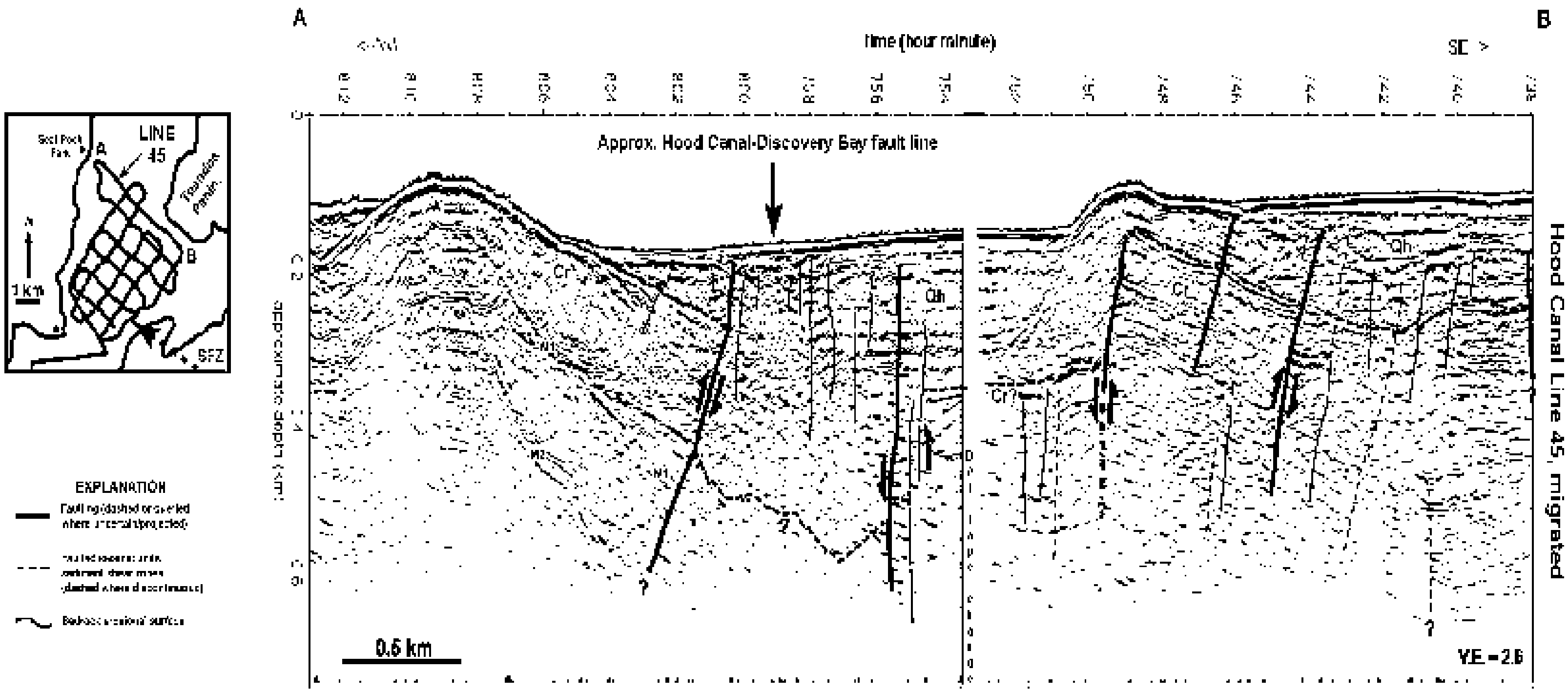

Figure 3. Interpreted Seismic profile, Line 45. This ~4 km-long profile starts SW of Oak Head, crosses Dabob Bay and ends ~1 km SE of Seal Rock beach (see "line 45," Figure 1). An asymmetric V-shaped valley can be seen in Dabob Bay infilled with 200 to 350 m of acoustically unstratified to weakly stratified Quaternary sediments. A 10–30 m-thick well-stratified surface layer overlies the basin fill. To the extreme upper left of Figure 3, east-dipping Crescent basalt can be traced ~1 km beneath the sediments where it is abruptly truncated. This faulted bedrock corresponds nicely with the Gower et al. (1985) fault trace. A deep sediment-filled graben structure occupies the center of Dabob Bay. Along the eastern side of Dabob Bay, uplifted and/or rotated Crescent blocks are draped by glacial landslide deposits from Toandos Peninsula. The peninsula's western shoreline may continue NE along defined by the upper edge of this rotated crustal block (?). Blind faults terminate within 50 m of the surface layer and sediment deformation features are pervasive beneath central Dabob Bay. Movement along bedrock fault planes below these sediments may have initiated these blind faults.

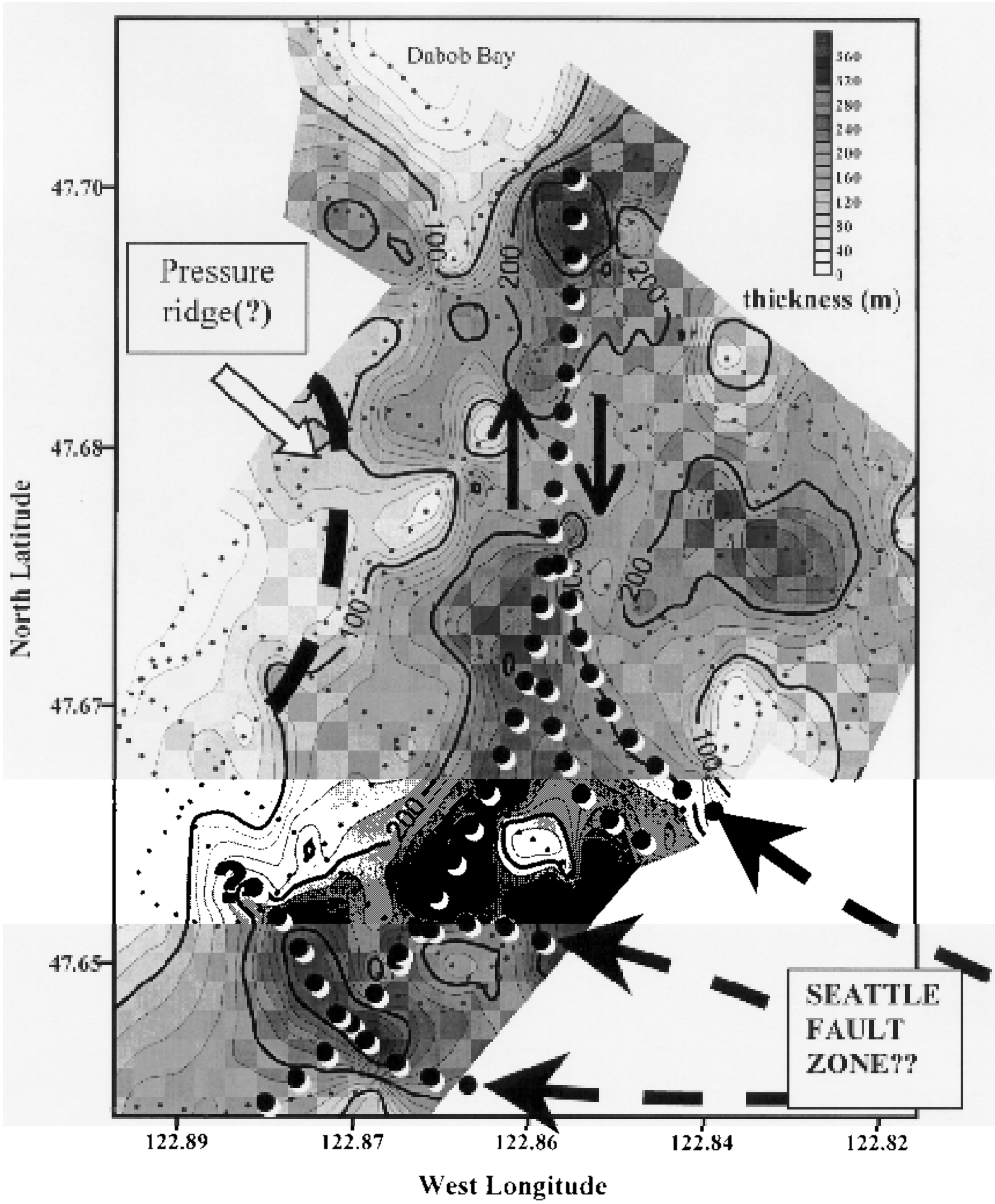

Figure 4. Isopach (sediment-thickness) map. This map details the thickness (in meters) of Quaternary sediment covering the faulted Crescent basalt over an approximate 25 km^2 area between Seal rock to the north and Quatsop Point to the south. The sediment cover generally thickens eastward varying from 0 to ~350 m. Toward the middle of the Hood Canal trough, the thicker sediment packets (>200 m) fill down-dropped crustal blocks trending very close to the Gower et al. (1985) fault trace. The northwest-trending closed contour sausage-shaped feature (~47.65N, 122.87W) may be a faulted zone crossing Hood Canal. The 380 m contour at the head of Dabob Bay represents the NE-trending graben structure noted on Figure 5 (trackline 45).

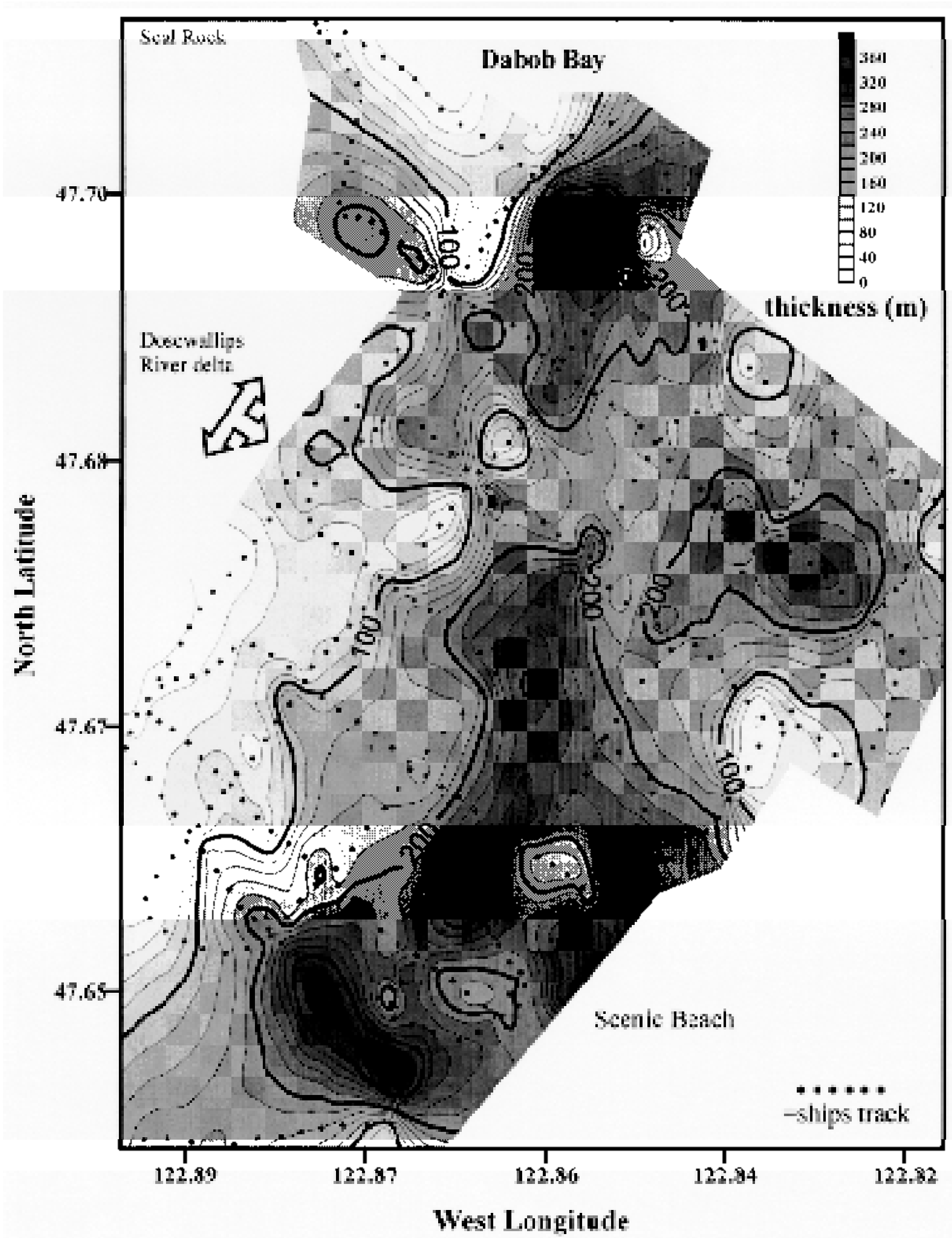

Figure 5. Interpreted fault map overlaid on Figure 4. This preliminary map shows a few of the many possible fault splay patterns joining the Hood Canal-Discovery Bay fault zone. The mapped pressure ridge structure was noted on four separate seismic profiles (none of which are shown in this report) and may be a segmented or en echelon structure. These are quite common with left bending or left-stepping dextral fault zones.

Conclusions

1. There is geophysical evidence for normal and strike-slip faulting in the Hood Canal and southern Dabob Bay area. This faulting pattern is generally consistent with the Gower et al. (1985) fault trace.

2. Quaternary sediment thickness in the ~25 km^2 mapped area varies from 0 to 380 m, with a general increase in thickness east and toward the canal centerline.
3. Blind faults terminating <30 m below the sediment/water interface may be co-seismic in nature; possibly related to displacement along the Seattle fault zone.
4. Fault splays of the Seattle fault zone may be present in Hood Canal and play a role in the development of anomalous isopach contours, pressure ridge structures, and sediment deformational patterns seen in Hood Canal.

References

Aprea, C., Unsworth, M., and Booker, J., 1998, Resistivity structure of the Olympic Mountains and Puget Lowlands: Geophysical Research Letters, v. 25, no. 1, pp. 109–112.

Atwater, B. F., and Moore, A. L., 1992, A tsunami about 1000 years ago in Puget Sound, Washington: Science, v. 258, pp. 1614–1616.

Babcock, R. S., Burmester, R. F., Engebretson, D. C., Warnock, A., and Clark, K. P., 1992, A rifted margin origin for the Crescent basalts and related rocks in the northern Coast Range Volcanic Province, Washington and British Columbia: Journal of Geophysical Research, v. 97, no. B5, pp. 6799–6821.

Booth, D. B., and Hallet, B., 1993, Channel networks carved by sub-glacial water: Observations and reconstruction in the eastern Puget Lowland of Washington: Geological Society of America Bulletin, v. 105, pp. 671–683.

Booth, D. B., 1994, Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation: Geology, v. 22, pp. 695–698.

Bucknam, R. C., Hemphill-Haley, E., and Leopold, E. B., 1992, Abrupt uplift within the past 1700 years at southern Puget Sound, Washington: Science, v. 258, pp. 1611–1613.

Danes, Z. F., Bonno, M. M., Brau, E., Gilham, W. D., Hoffman, T. F., Johansen, D., Jones, M. H., Malfait, B., Masten, J., and Teague, G. O., 1965, Geophysical investigations of the southern Puget Sound area, Washington: Journal of Geophysical Research, v. 70, no. 22, pp. 5573–5580.

Dewberry, S. R., 1996, Crustal and upper mantle structure for the Pacific Northwest from an analysis of short-period teleseismic network data. Ph.D. thesis, University of Washington, 167 p.

Eyles, N., Mullins, H. T., and Hine, A. C., 1990, Thick and fast: Sedimentation in a Pleistocene fiord lake of British Columbia, Canada: Geology, v. 18, pp. 1153–1157.

Finn, C. A., 1990, Geophysical constraints on Washington convergent margin structure: Journal of Geophysical Research, v. 95, no. 12 pp. 19,533–19,546.

Finn, C. A., and Stanley, W. D., 1997, Something old, something new, something borrowed, something blue—a new perspective on seismic hazards in Washington using aeromagnetic data: Washington Geology, 25(2): 3–7.

Gower, H. D., Yount, J. C., and Crosson, R. S., 1985, Seismotectonic map of the Puget Sound region, Washington: U. S. Geological Survey, scale 1:250,000.

Gower, H. D., and Yount, J. C., 1991, Bedrock geologic map of the Seattle 30' by 60' Quadrangle, Washington: U. S. Geological Survey, scale 1:100,000.

Harding, S. T., Barnhard, T. P., and Urban, T. C., 1988a, Preliminary data from the Puget Sound multi-channel seismic reflection survey: U. S. Geological Survey, Open File Report 88-0698, pp. 7, 17 sheets.

Harding, S. T., Urban, T. C., and Barnhard, T. P., 1988b, Preliminary evidence of possible Quaternary faulting in Puget Sound, Washington, from a multichannel marine seismic reflection survey: U. S. Geological Survey, Open File Report 88-0541.

Jacoby, G. C., Williams, P. L., and Buckley, B. M., 1992, Tree ring correlation between prehistoric landslides and abrupt tectonic events in Seattle, Washington: Science, v. 258, pp. 1621–1623.

Johnson, S. Y., Potter, C. J., and Armentrout, J. M., 1994, Origin and evolution of the Seattle fault and Seattle basin, Washington: Geology, v. 22, no. 1, pp. 71–74.

Johnson, S. Y., Potter, C. J., Armentrout, J. M., Miller, J. J., Finn, C., and Weaver, C. S., 1996, The southern Whidbey Island fault; an active structure in the Puget Lowland, Washington: Geological Society of America Bulletin, v. 108, no. 3, pp. 334–354.

Karlin, R. E., and Abella, S. E. B., 1996, A history of Pacific Northwest earthquakes recorded in Holocene sediments from Lake Washington: Journal of Geophysical Research, v. 101, no. B3, pp. 6137–6150.

Mullins, H. T., Eyles, N., and Hinchey, E. J., 1990, Seismic reflection investigations of Kalamalka lake: a "fiord lake" on the Interior Plateau of southern British Columbia: Canadian Journal of Earth Science, v. 27, pp. 1225–1235.

Pratt, T. L., Johnson, S. Y., Potter, C. J., Stephenson, W. J., and Finn, C., 1997, Seismic reflection images beneath Puget Sound, western Washington State: The Puget Lowland thrust sheet hypothesis: Journal of Geophysical Research, v. 102, no. B12, pp. 27,469–27,489.

Schuster, R. L., Logan, R. L., and Pringle, P. T., 1992, Prehistoric rock avalanches in the Olympic Mountains, Washington: Science, v. 258, pp. 1620–1621.

Snavely, P. D. J., and MacLoed, N. S., 1974, Yachats basalt; an upper Eocene differentiated volcanic sequence in the Oregon Coast Range: Journal of Research of the U. S. Geological Survey, v. 2, no. 4, pp. 395–403.

Symons, N. P., and Crosson, R. S, 1997, Seismic velocity structure of the Puget Sound region from 3-D non-linear tomography, University of Washington, Seattle, Geophysics program: unpublished manuscript, pp. 6.

Tabor, R. W., and Cady, W. M., 1978, The structure of the Olympic Mountains, Washington-Analysis of a subduction zone: Geological Survey Professional Paper 1033, pp. 25.

Thorson, R. M., 1996, Earthquake recurrence and glacial loading in western Washington: Geological Society of America Bulletin, v. 108, no. 9, pp. 1182–1191.

Wang, K., Taimi, M., Rogers, G. C., and Hyndman, R. D., 1995, Case for very low coupling stress on the Cascadia subduction fault: Journal of Geophysical Research, v. 100, no. B7, pp. 12,907–12,918.

Wilson, J. R., Bartholomew, M. J., and Carson, R. J., 1979, Late Quaternary faults and their relationship to tectonism in the Olympic Peninsula, Washington: Geology, v. 7, pp. 235–239.

Yount, J. C., Dembroff, G. R., and Barats, G. M., 1985, Map showing depth to bedrock in the Seattle 30’ by 60’ Quadrangle, Washington: U. S. Geological Survey, scale 1:100,000.